

Shattering by turbulence as a production source of very small grains

Hiroiyuki Hirashita*

Institute of Astronomy and Astrophysics, Academia Sinica, P.O. Box 23-141, Taipei 10617, Taiwan

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ABSTRACT

The origin of grain size distribution in the interstellar medium is one of the most fundamental problems in the interstellar physics. In the Milky Way, smaller grains are more abundant in number, but their origins are not necessarily specified and quantified. One of the most efficient drivers of small grain production is interstellar turbulence, in which dust grains can acquire relative velocities large enough to be shattered. Applying the framework of shattering developed in previous papers, we show that small ($a \lesssim 0.01 \mu\text{m}$) grains reach the abundance level observed in the Milky Way in $\sim 10^8$ yr (i.e. within the grain lifetime) by shattering in warm neutral medium. We also show that if part of grains experience additional shattering in warm ionized medium, carbonaceous grains with $a \sim 0.01 \mu\text{m}$ are redistributed into smaller sizes. This could explain the relative enhancement of very small carbonaceous grains with $a \sim 3\text{--}100 \text{ \AA}$. Our theory also explains the ubiquitous association between large grains and very small grains naturally. Some tests for our theory are proposed in terms of the metallicity dependence.

Key words: dust, extinction — galaxies: evolution — galaxies: ISM — turbulence

1 INTRODUCTION

Formation and evolution of dust grains is one of the fundamental problems in the interstellar physics. In particular, the grain size distribution largely affects the opacity (or extinction) of interstellar medium (ISM). Mathis, Rumpl, & Nordsieck (1977, hereafter MRN) reproduced the extinction curve of the Milky Way by a mixture of silicate and graphite with a size distribution of $n(a) \propto a^{-3.5}$, where $n(a) da$ is the number density of grains with radii between a and $a + da$. More recently, Weingartner & Draine (2001) and Li & Draine (2001) have derived more detailed grain size distribution, finding that an enhancement of small carbonaceous grains, especially polycyclic aromatic hydrocarbons (PAHs), is required to reproduce the mid-infrared (MIR) spectrum in the Milky Way.

The grain size distribution reflects the physical processes in grain formation and evolution (O'Donnell & Mathis 1997). Dust grains are not only produced and ejected by supernovae (SNe) (e.g. Kozasa, Hasegawa, & Nomoto 1989) and asymptotic giant branch (AGB) stars (e.g. Gail, Keller, & Sedlmayr 1984) but also processed in the ISM. Hirashita & Yan (2009, hereafter HY09) show that shattering occurs efficiently in diffuse ISM, where grains are accelerated by magnetohydrodynamic (MHD) turbulence. In particular, turbulence in warm ionized medium (WIM) can drive shattering of dust grains in $\lesssim 10$ Myr, producing small grains efficiently (Hirashita et al. 2010). Therefore, shattering should play a significant role in determining the grain size distribution. Shattering

also occurs efficiently in supernova shocks (Borkowski & Dwek 1995; Jones, Tielens, & Hollenbach 1996).

There are some indications that the grains formed and supplied to the ISM are biased to large sizes. As Nozawa et al. (2007) show, the grains ejected from SNe II are biased to large sizes because they suffer from the destruction in the shocked region before being ejected into the ISM (cf. Bianchi & Schneider 2007). The grain radius is typically around $a \sim 0.1 \mu\text{m}$. The typical size of grains condensed in AGB stars is also suggested to be large ($a \sim 0.1 \mu\text{m}$) from the observations of spectral energy distributions (Groenewegen 1997; Gauger et al. 1999), although Hofmann et al. (2001) show that the grains are not single-sized. Moreover, in the Milky Way and other systems whose metallicity is around solar, the major part of the dust mass comes from the grain growth by accretion of heavy elements in interstellar clouds (e.g. Dwek 1998; Draine 2009). Not only the grain growth by accretion but also coagulation in dense clouds causes a strong depletion of small grains (HY09). To summarize, the grains supplied from molecular clouds or stars should be biased to the largest size range, $a \sim 0.1 \mu\text{m}$.

If the major part of dust grains supplied are large, the origin of small grains is worth investigating seriously. Here we focus on shattering as a production source of small grains. Specifically, we examine if large grains with $a \sim 0.1 \mu\text{m}$ are efficiently redistributed into small ($\lesssim 0.01 \mu\text{m}$) grains by shattering driven by interstellar turbulence, which is ubiquitous in the ISM. Hirashita et al. (2010) have shown that shattering in the WIM produced by starburst activities can efficiently produce small grains from large grains supplied from SNe II. In this Letter, we discuss shattering in a more general context by showing that turbulence plays a fundamental role in supplying small grains in more quiescent environments such as in

* E-mail: hirashita@asiaa.sinica.edu.tw

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warm neutral medium (WNM) covering a large fraction of the ISM in the Milky Way. Shattering in supernova shocks should also be considered (Jones et al. 1996), but the inclusion of this process into our framework is left for future work. Throughout this paper, grains are assumed to be spherical, and the words, ‘large’ and ‘small’, are used for grain radii of $a \sim 0.1 \mu\text{m}$ (\sim the largest size range in MRN) and $a \lesssim 0.01 \mu\text{m}$, respectively.

2 METHOD

2.1 Initial condition

To examine interstellar shattering induced by turbulence as a mechanism of producing small grains from large grains, we assume the initial grain size distribution to be dominated by large grains. This ‘initial’ grain size distribution effectively represents not only one at the formation in stellar ejecta but also one after the grain growth in cold clouds in the ISM. The functional form of the initial grain size distribution is represented by a log-normal distribution, $n(a) = n_{\text{ini}}(a)$:

$$n_{\text{ini}}(a) = \begin{cases} \frac{C}{a} \exp \left\{ -\frac{[\ln(a/a_0)]^2}{2\sigma^2} \right\} & (a_{\min} \leq a \leq a_{\max}) \\ 0 & (\text{otherwise}), \end{cases} \quad (1)$$

where C is the normalizing constant determined by equation (2), a_0 and σ are the central grain radius and the standard deviation of the log-normal distribution, respectively, and a_{\min} and a_{\max} are the minimum and the maximum grain sizes, respectively. We adopt $a_0 = 0.1 \mu\text{m}$ according to the above argument in Introduction, $a_{\min} = 3.5 \text{ \AA}$, $a_{\max} = 1 \mu\text{m}$, and $\sigma = 0.6$. The selection of σ is based on the size dispersion of large Si and C grains as calculated by Nozawa et al. (2007).

We consider two dust species, silicate and graphite, and distribute each species according to the above size distribution. The normalizing constant C is determined for each species by

$$\mathcal{R} m_{\text{H}} n_{\text{H}} = \int_0^\infty \frac{4\pi}{3} a^3 \rho_{\text{gr}} n_{\text{ini}}(a) da, \quad (2)$$

where \mathcal{R} is the dust-to-hydrogen mass ratio (i.e. dust abundance relative to hydrogen), n_{H} is the hydrogen number density, and ρ_{gr} is the grain material density (3.3 g cm^{-3} and 2.2 g cm^{-3} for silicate and graphite, respectively). We adopt $\mathcal{R} = 4.0 \times 10^{-3}$ and 3.4×10^{-3} for silicate and graphite, respectively, according to the typical Galactic dust-to-gas ratio (HY09).

2.2 Shattering

The evolution of grain size distribution by shattering is calculated based on HY09, whose formulation is taken from Jones et al. (1994, 1996). The shattering equation is calculated for silicate and graphite separately to avoid the complexity caused by the collision between different species. The grain–grain collision rate is estimated based on the grain velocity as a function of grain size (Section 2.3), and if the relative velocity is higher than the shattering threshold (2.7 and 1.2 km s^{-1} for silicate and graphite, respectively), the grains are redistributed into smaller grains according to the size distribution of shattered fragments, which is assumed to be power-law ($\propto a^{-3.3}$; note that the results are not very sensitive to the exponent; Jones et al. 1996; Hirashita et al. 2010).

HY09 consider shattering in various ISM phases. Among them, we first consider WNM, which occupies a significant fraction of the interstellar space. We also treat additional shattering in WIM. Although WIM occupies a small fraction in the ISM, the short time-scale of shattering in WIM (HY09) can make a significant imprint on the grain size distribution.

2.3 Grain velocities

The grain velocity as a function of grain radius a is taken from Yan et al. (2004), who considered the grain acceleration by hydrodrag and gyroresonance (resonance which occurs when the Doppler-shifted frequency of the MHD wave in the grain’s guiding centre rest frame is a multiple of the gyrofrequency) based on Yan & Lazarian (2003) and calculated the grain velocities achieved in various ISM phases. They adopted the following physical conditions: in WNM $n_{\text{H}} = 0.3 \text{ cm}^{-3}$, $T = 6000 \text{ K}$, $n_e = 0.03 \text{ cm}^{-3}$, $G_{\text{UV}} = 1$, $V_A = 20 \text{ km s}^{-1}$, $L = 100 \text{ pc}$ (T is the gas temperature, n_e is the electron number density, G_{UV} is the UV radiation field normalized to the typical Galactic value in the solar neighbourhood, V_A is the Alfvén speed, and L is the injection scale for turbulence), and in WIM $n_{\text{H}} = 0.1 \text{ cm}^{-3}$, $T = 8000 \text{ K}$, $n_e = 0.0991$, and the same values as in WNM for the other quantities.

Large ($a > 0.1 \mu\text{m}$) grains are mainly accelerated by gyroresonance. Thus, in considering shattering of large grains, gyroresonance is the key process. Although the grain charge strongly depends on gas density, electron fraction, and UV flux, the velocities of large grains do not strongly depend on the grain charge as mentioned in Hirashita & Yan (2009): The acceleration by gyroresonance increases with the grain charge, but the acceleration duration (the hydrodrag time-scale) decreases with the grain charge (Yan & Lazarian 2003). Thus, as for the small grain production from large ($a \gtrsim 0.1 \mu\text{m}$) grains, the results in this paper is insensitive to the grain charge. As shown in Hirashita et al. (2010), the velocities of large grains do not sensitively depend on the gas density. The grain velocity may depend on the electron fraction, since the damping of turbulent motion depends on it. The dependence on the ionization fraction is roughly bracketed by the velocities in WNM and WIM. Since the velocities of large grains are similar in these two phases, they are not affected by the electron fraction. The remaining uncertainty in the model comes from the magnetic field (or the Alfvén velocity), which is discussed in Section 3.1.

3 RESULTS

3.1 Shattering in WNM

The evolution of grain size distribution by shattering in WNM is shown in Fig. 1. As a reference, the MRN size distribution ($n(a) \propto a^{-3.5}$ with $a_{\min} = 10^{-3} \mu\text{m}$ and $a_{\max} = 0.25 \mu\text{m}$) is also shown. We observe that shattering redistributes the large grains into small sizes on a time-scale of $\lesssim 100 \text{ Myr}$, which is shorter than the grain lifetime in the ISM (a few $\times 10^8 \text{ yr}$; Jones et al. 1996). Moreover, the grain size distribution approaches the MRN size distribution, which indicates that shattering is efficient enough to enrich the small grains up to the abundance level in the Milky Way.

Since the time-scale of shattering is inversely proportional to the gas density and the dust-to-gas ratio, we can summarize our result by the following estimate of a time-scale, τ_{shat} , on which shattering in turbulence supplies small grains to a level compatible

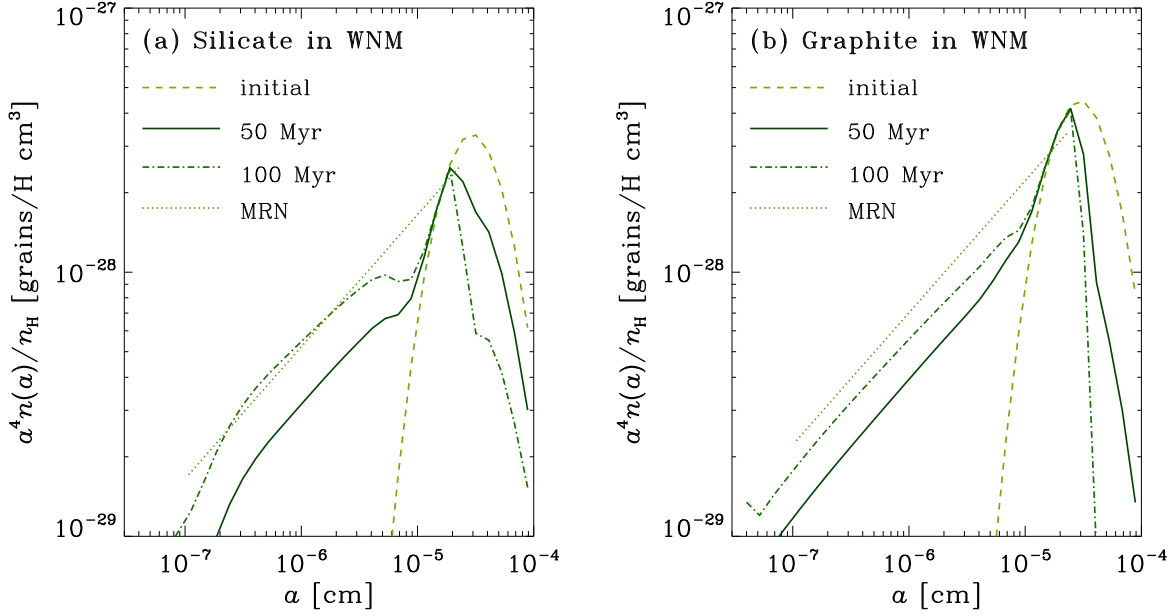


Figure 1. Grain size distributions in WNM. The grain size distribution is divided by n_H and multiplied by a^4 to show the grain mass distribution per $\log a$ and per hydrogen nucleus. Two grain species, (a) silicate and (b) graphite, are shown. The solid and dot-dashed lines indicate the grain size distribution at $t = 50$ and 100 Myr, respectively, and the dashed line shows the initial log-normal distribution. The dotted line shows the MRN size distribution.

with the MRN size distribution:

$$\tau_{\text{shat}} \sim 10^8 (\mathcal{R}/\mathcal{R}_0)^{-1} (n_H/0.3 \text{ cm}^{-3})^{-1} \times (a_0/0.1 \text{ } \mu\text{m}) (V_{\text{shat}}/20 \text{ km s}^{-1})^{-\alpha} \text{ yr}, \quad (3)$$

where \mathcal{R}_0 is the dust-to-hydrogen mass ratio assumed in this paper for the Galactic environment, and V_{shat} is the typical relative velocity among the grains. The dependence on a_0 comes from the grain collision time-scale with a fixed total grain mass. For the grain velocity, $V_{\text{shat}} \sim V_A$ can be achieved after gyroresonance. The exponent α is 1 if small grain production is only governed by the collision rate. We test several cases where we have artificially changed the velocities achieved by large grains, and α proves to be ~ 2 around $V_{\text{shat}} \sim 5\text{--}30 \text{ km s}^{-1}$. As mentioned in Section 4.2, 30 per cent of the small grains are produced by the collision between small and large grains; in this case, cratering occurs in large grains, and α becomes larger than 1 because of the velocity dependence of the cratered volume.

Shattering of large grains in cold neutral medium (CNM) may also be important if a significant fraction of the ISM is in a cold phase (McKee 1989). A lower velocity ($\sim 1\text{--}2 \text{ km s}^{-1}$; Yan et al. 2004) achieved in CNM is compensated by a large density ($\sim 30 \text{ cm}^{-3}$), so that the shattering time-scale in CNM is similar to that in WNM (HY09) for graphite. Because of a larger shattering threshold velocity of silicate, silicate grains may not be shattered in CNM.

3.2 Shattering in WIM

In this Letter, we treat shattering in WIM as an additional effect, since larger fraction of the volume is occupied by neutral medium. We adopt the results at 100 Myr in Section 3.1 for the initial condition. In Fig. 2, we show the grain size distribution after 1 and 3 Myr of shattering in WIM. By shattering in WIM, not only large grains but also relatively small grains with $a \sim 0.01\text{--}0.1 \text{ } \mu\text{m}$

are destroyed efficiently. Thus, shattering in WIM may be an effective mechanism to enhance the abundance of small grains at $a \lesssim 0.01 \text{ } \mu\text{m}$. This is further discussed in Section 4.1 in terms of the PAH abundance.

4 DISCUSSION

4.1 Comparison with the Galactic grain size distributions

This paper provides an experimental investigation as to whether the mean abundance of small grains derived from the mean extinction by MRN can be achieved by shattering. Observationally, the grain size distribution is derived from the extinction curve along a line of sight, which could cross not only diffuse ISM but also clouds. The typical time-scale of the phase exchange between diffuse ISM and clouds is less than 100 Myr (Ikeuchi 1988), shorter than the grain lifetime. Therefore, the grains processed in WNM are mixed among the ISM phases. If this is true, we can directly compare the results obtained in this paper with the grain size distribution derived observationally from the extinction curve. If we consider the existence of the ISM phases other than WNM, the shattering time-scale should be modified as $\tau_{\text{shat}}/f_{\text{WNM}}$, where f_{WNM} is the fraction of time spent in WNM. We assume that f_{WNM} is not much smaller than 1.

As shown in the previous section, shattering in WNM redistributes large grains into small grains in the grain lifetime so that the abundance of small grains becomes consistent with the MRN grain size distribution. Therefore, shattering in turbulent ISM is a strong candidate for the dominant production mechanism of small grains. The short shattering time-scale ($\tau_{\text{shat}} \sim 100 \text{ Myr}$) indicates that the loss of large grains by shattering is likely to be balanced with the dust growth in dense clouds, not by the injection of large grains from stars (see Draine 2009 for the time-scales of these processes).

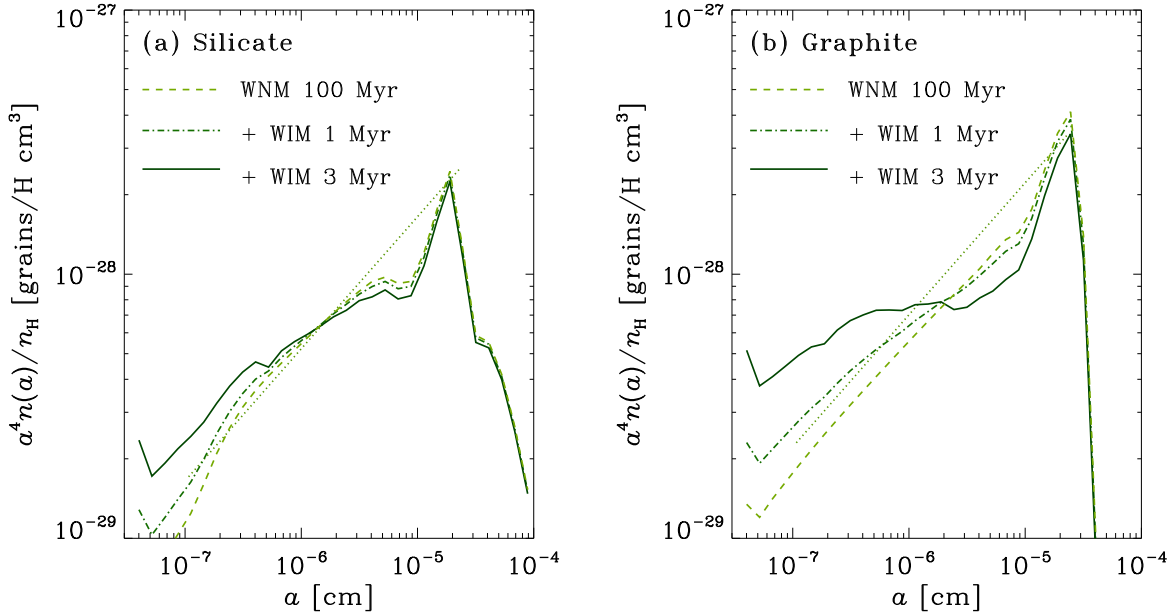


Figure 2. Same as Fig. 1 but with additional shattering in WIM. The shattering durations in WIM are 1 and 3 Myr for the dot-dashed and solid lines, respectively. The dashed line shows the initial (i.e. processed by shattering in WNM for 100 Myr; same as the dot-dashed lines in Fig. 1), and the dotted line presents the MRN size distribution.

Shattering in WIM destroys not only large grains but also relatively small grains very efficiently. Thus, some imprints of WIM on the grain size distribution may be seen for the Galactic grain size distribution. In Fig. 2, we indeed observe the enhancement of small grains at $a < 100 \text{ \AA}$ for graphite. The enhancement of very small grains is relatively minor for silicate, since silicate is harder to shatter than graphite. It is interesting to point out that the enhancement of very small grain abundance is more pronounced for carbonaceous species than silicate species according to Weingartner & Draine (2001) and Li & Draine (2001). Li & Draine (2001) have shown that an excess in the PAH abundance at $a < 100 \text{ \AA}$ relative to the extension of the MRN size distribution is required to reproduce the PAH emission strength in the Milky Way. Such an excess also keeps the consistency with the extinction curve (Weingartner & Draine 2001). Strictly speaking, small PAHs should be treated as molecules as done by Micelotta, Jones, & Tielens (2010). Nevertheless, we expect that PAHs once produced are not much affected by shattering in turbulence, since small grains (also PAHs) are coupled with small scale (i.e. low velocity) turbulence.

4.2 Coexistence of large and small grains

Our hypothesis investigated in this paper, that is, that shattering governs the production of very small grains, naturally explains the ubiquitous coexistence of large and small grains. Indeed, in the Galactic environment, the spatial distribution of very small grains radiating in the MIR and that of large grains emitting in the far infrared (FIR) shows a tight correlation (Shibai, Okumura, & Onaka 1999). Also the PAH emission is always associated with the dust continuum (Onaka et al. 1999). Moreover, the FIR colours of extragalactic objects are consistent with the Galactic FIR colours (Hibi et al. 2006), which implies that the grain size distribution is

not very different. The fact that observational MIR to FIR SEDs can be described by a small numbers of parameters (Dale et al. 2001; Nagata et al. 2002) also implies that there is a ubiquitous mechanism for determining the grain size distribution. Finally, shattering occurs predominantly in diffuse neutral and ionized medium, which is consistent with the diffuse nature of the 70 \mu m excess coming from very small grains (Bernard et al. 2008).

We have shown that even if there are only large grains, the supply of small grains are efficient enough. In other words, shattering by interstellar turbulence always provides a path for small grain production. After an enough number of small grains are produced, it would be more reasonable to consider that the grains supplied from stars or dense clouds are well mixed with the MRN-like size distribution. The shattering under an MRN size distribution is considered in HY09, who also obtain a similar time-scale for shattering. The similarity in the time-scale between our case and HY09's is explained as follows: In WNM, only large grains acquire velocities large enough for shattering. Thus, a collision with a large grain is the only way for a grain to be shattered. Let us consider a 'projectile' with size a colliding with a large grain with size a_{large} . The contribution from projectiles with sizes between a and $a + da$ to shattering of the large grain is roughly proportional to $\pi a_{\text{large}}^2 V_{\text{shat}} n(a) \mathcal{V} da$, where \mathcal{V} is the shattered volume. If the projectile is large, \mathcal{V} is large (in particular, if $a \sim 0.1 \text{ \mu m}$, \mathcal{V} is equal to the entire volume of the large grain). Thus, larger projectiles have larger impacts on the large grain. Indeed, if we consider shattering among large ($a > 0.08 \text{ \mu m}$) grains only, the production rate of grains with $a \sim 0.01 \text{ \mu m}$ becomes only 30 per cent less (i.e. 30 per cent of small grain production is attributed to the collisions between small and large grains). Since $n(a)$ is similar between our initial distribution and the MRN at large sizes, we obtain a similar shattering time-scale to HY09.

4.3 Metallicity dependence

Since the shattering time-scale is inversely proportional to the dust-to-gas ratio (equation 3), it is expected that the abundance of very small grains is low in dust-poor (metal-poor) galaxies. However, as pointed out by Hirashita & Ichikawa (2009), detection of infrared dust emission from low-metallicity objects could be biased to dense systems. In such dense environments, shattering is enhanced. Consequently, the MIR radiation from very small grains may become strong (Galliano et al. 2005; Engelbracht et al. 2008). Thus, dust emission from diffuse (low-density) low-metallicity system can be a strong test for our theory: if the MIR continuum is suppressed in such a system, our hypothesis that shattering is the production source of very small grains is supported.

The production of small grains by shattering also indicates that the materials of small grains reflect those of original large grains. The formation mechanism of large grains should depend on metallicity: The production of large grains by accretion of heavy elements in molecular clouds is inefficient in low metallicity. Thus, stellar production of grains should be the dominant source of large grains in low-metallicity environments (e.g. Matsuura et al. 2008; Galliano, Dwek, & Charnial 2008). Considering that molecular clouds are the site of various chemical reactions, large grains formed by stars and those grown in molecular clouds could be chemically different. The metallicity dependence of MIR emission properties, especially that of PAH emission (e.g. Smith et al. 2007; Draine et al. 2007), may reflect the different properties of original large grains in terms of metallicity. Also if there is a spatial variation of production sources of large grains, spatial variation of very small grains and PAHs may also be present as observed by Bernard et al. (2008) and Paradis et al. (2009).

5 CONCLUSION

We have theoretically investigated interstellar shattering of large grains ($a \sim 0.1 \mu\text{m}$) as a production source of small grains. We have shown that by shattering in WNM the abundance of small grains reaches the level consistent with the MRN size distribution in $\sim 10^8$ yr (i.e. in the grain lifetime). Shattering in WIM additionally destroys grains with $a \sim 0.01 \mu\text{m}$ and redistribute them into smaller sizes. This effect is more pronounced for the carbonaceous grains, and can explain the enhancement of very small carbonaceous grains (or PAHs) with $a < 100 \text{ \AA}$ as indicated observationally by Li & Draine (2001). Since turbulence is ubiquitous in the ISM, our theory naturally explains the strong MIR–FIR correlation observed generally for galaxies.

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